Muons from strangelets

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The hypothesis is discussed that muon bundles of extremaly high multiplicity observed recently by ALEPH detector (in the dedicated cosmic-ray run) can originate from the strangelets colliding with the atmosphere.

1. INTRODUCTION

In the astrophysical literature [1] one can find a number of phenomena which can be regarded as a possible manifestation of the existence of the so called *Strange Quark Matter* (SQM) (in the form of lumps called strangelets), extremaly interesting possibility of a possible new stable form of matter. They include, among others, anomalous cosmic ray burst from *Cygnus X-3*, extraordinary high luminosity gamma-ray bursts from the *supernova remnant N49* in the Large Magellanic Cloud or *Centauro* type events. There are also several reports suggesting direct candidates for the SQM. In particular, anomalous massive particles, which can be interpreted as strangelets, have been apparently observed in cosmic ray experiments [1]. All this makes a search for other possible candidates or signals for SQM extremaly interesting topic.

Proceeding along this line we would like to bring ones attention to the recent (still unpublished, however) data from the cosmic ray run of the ALEPH detector at CERN-LEP experiment. The hypothesis which we shall discuss in what follows is that, if confirmed, the muon bundles of extremely high multiplicity observed recently by ALEPH in its dedicated cosmic-ray run [2] can originate from the strangelets propagating through the atmosphere and interacting with the air nuclei.

2. MUON BUNDLES FROM CosmoLEP

Why the CosmoLEP data are potentially so important? The reson is twofold. First, the studies of high multiplicity cosmic muon events (called muon bundles) is potentially very important source of information about the composition of primary cosmic rays. It is because muons transport (in essentially undisturbed way) significant information on the first interaction of the cosmic ray particle with atmosphere. In comparison electromagnetic cascades are more calorimetric in nature and less sensitive to any model uncertainties, which could be important for establishing the primary spectrum. The second point has to do with the fact that multi-muon bundles have never been studied with such precise detectors as provided by LEP program at CERN, nor have they been studies at such depth as at CERN [3]. The underground location of the LEP detectors (between 30 and 140 meters) is ideal for the muon based experiments because the corresponding muon momentum cut-off is then between 15 and 70 GeV, i.e., in the most sensitive range from the point of view of the primary interaction, where interaction and decay probabilities are equal at the starting point of the cascade.

The present situation is following. Data archives from the ALEPH runs have revealed a substantial collection of cosmic ray muon events. More than $3.7 \cdot 10^5$ muon events have been recorded in the effective run time 10^6 seconds. Multi-muon events observed in the 16 m^2 time-

projection chamber with momentum cut-off 70 GeV have been analysed and good agreement with the Monte Carlo simulations (performed using *Corsika* code [4]) obtained for multiplicities N_μ between 2 and 40. However, there are 5 events with unexpectedly large multiplicities N_μ (up to 150) which rate cannot be explained, even assuming pure iron primaries. They will be our central point of interest here.

3. SOME FEATURES OF STRANGELETS

For completeness we shall summarize now features of strangelets and their propagation through the atmosphere, which will be relevant to our further discussion. The more detailed information can be found in [5]. Typical SQM consists of roughly equal number of up (u), down (d) and strange (s) quarks and it has been argued to be the true ground state of QCD [6,7]. For example, it is absolutely stable at high mass number A (excluding weak interaction decays of strange quarks, of course) and it would be more stable than the most tightly bound nucleus as iron (because the energy per barion in SQM could be smaller than that in ordinary nuclear matter). On the other hand it becomes unstable below some critical mass number A_{crit}, which is of the order of $A_{crit} = 300 - 400$, depending on the various choices of relevant parameters [7]. At this value of A the separation energy, i.e., the energy which is required to remove a single barion from a strangelets starts to be negative and strangelet decays rapidly by evaporating neutrons.

In [5] we have demonstrated that the geometrical radii of strangelets $R = r_0 A^{1/3}$ are comparable to those of ordinary nuclei of the corresponding mass number A (i.e., in both cases r_0 are essentially the same). We have shown at the same place how it is possible that such big objects can apparently propagate very deep into atmosphere. The scenario proposed and tested in [5] was that after each collision with the atmosphere nucleus strangelet of mass number A_0 becomes a new one with mass number approximately equal $A_0 - A_{air}$ and this procedure continues unless either strangelet reaches Earth or (most probably) disintegrates at some depth h of atmosphere reaching $A(h) = A_{crit}$.

This results, in a first approximation (in which $A_{air} << A_{crit} < A_0$), in the total penetration depth of the order of

$$\Lambda \simeq \frac{4}{3}\lambda_{N-air}\left(\frac{A_0}{A_{air}}\right)^{1/3} \quad (1)$$

where λ_{N-air} is the usual mean free path of the nucleon in the atmosphere.

4. RESULTS

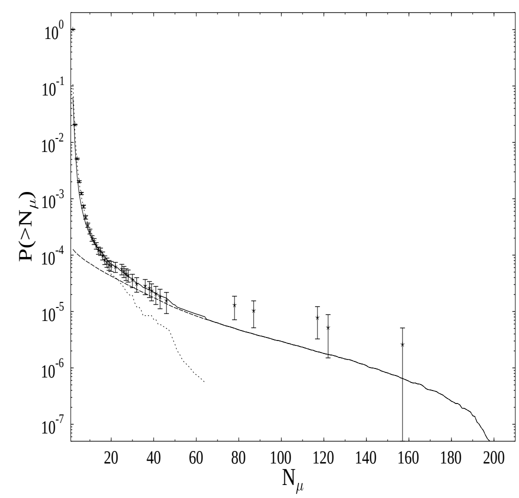

Fig.1 Integral multiplicity distribution of muons for the CosmoLEP data (stars), Monte Carlo simulations for primary nuclei with "normal" composition (dotted line) and for primary strangelets with $A = 400$ (broken line). Full line shows the summary (calculated) distribution.

This is the picture we shall use to estimate the production of muon bundles produced as result of interaction of strangelets with atmospheric nuclei. We use for this purpose the SHOWERSIM [8] modular software system specifically modified for our present purpose. Monte Carlo program describes the interaction of the primary particles at the top of atmosphere and follows the resulting

electromagnetic and hadronic cascades through the atmosphere down to the observation level. Muons with momenta exceeding 70 GeV are then registered in the sensitive area of 16 m^2 (randomly scattered in respect to the shower axes). Primaries initiated showers were sampled from the usual power spectrum $P(E) \propto E^{-\gamma}$ with the slope index equal to $\gamma = 2.7$ and with energies above $10 \cdot A$ TeV.

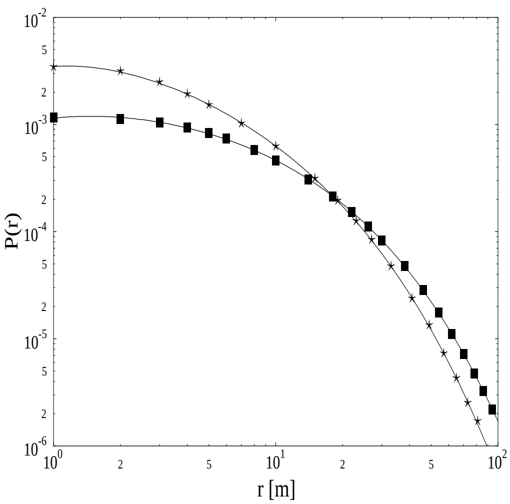

Fig.2 Lateral distribution of muons in the bundles with multiplicities $90 < N_\mu < 110$, which originated from primary proton (stars) and primary strangelet with mass number $A = 400$ (squares) (both with energy 10^4 TeV per particle).

The integral multiplicity distribution of muons from ALEPH data are compared with our simulations in Fig. 1. We have used here the so called "normal" chemical composition of primaries [9] with 40 % of protons, 20 % of helium, 20 % of C-N-O mixture, 10 % of Ne-S mixture and 10 % of Fe. It can describe low multiplicity ($N_\mu \leq 20$) region only. On the other hand, muon multiplicity from strangelet induced showers are very broad. As can be seen, the small amount of strangelets (with the smallest possible mass number $A = 400$, i.e., the one being just above the estimated critical one estimated to be $A_{crit} \sim 320$ here) in the primary flux can accomodate experimental data. Taking into account the registration efficiency for different types of primaries one can estimate the amount of strangelets in the primary cosmic flux. To describe the observed rate of high multiplicity events one needs the relative flux of strangelets $F_S/F_{total} \simeq 2.4 \cdot 10^{-5}$ (at the same energy per particle).

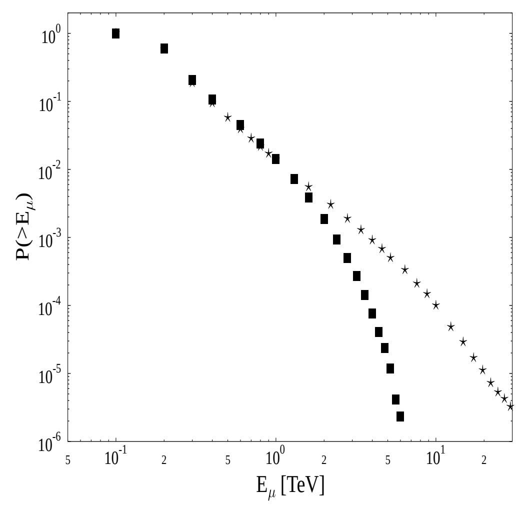

Fig.3 Energy distribution of muons in the bundles with multiplicities $90 < N_\mu < 110$, which originated from primary proton (stars) and primary strangelet with mass number $A = 400$ (squares) (both with energy 10^4 TeV per particle).

Fig. 2 shows the lateral distribution and Fig. 3 the energy distribution of muons in the bundles. They allow us to test the origin of high multiplicity events. Note that, in order to obtain high N_μ tail from normal nuclei only, one needs much higher primary energies per nucleon than in the case where strangelets were also added. Distribution of muons from strangelets is broader and their energy spectrum softer in comparison to events with the same N_μ induced by protons. It is interesting to observe that the high multiplicity events discussed here (with $N_\mu \simeq 110$ recorded on 16 m^2) correspond to ~ 5600 muons with $E_\mu \geq 70$ GeV (or 1000 muons with energies

above 220 GeV). These numbers are in suprisingly good agreement with results from other experiments like Baksan Valley, where 7 events with more than 3000 muons of energies exceeding 220 GeV were observed [10].

5. CONCLUSIONS

To recollect: we have demonstrated that the recently observed extremaly high multiplicity of muons can be most adequately described by relatively minuite (of the order of $\sim 2.4 \cdot 10^{-5}$ of total primary flux) admixture of strangelets of the same total energy. This is precisely the flux we have estimated some time ago [5] when interpreting direct candidates for strangelets and is fully consistent with existing experimental estimations provided by [11]. It accomodates also roughly the observed flux of Centauro events as was shown in [12]. The CosmoLEP studies of muli-muon bundles will therefore significantly improve our understanding of the nature and importance of the SQM candidates.

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